Summary of Research on Green Manure Cover Crops and Irrigated Wheat (2020–2022)

Introduction

Wheat is a cornerstone of food security, yet its productivity is often constrained by soil fertility decline, water limitations, and rising input costs. Green manure cover crops offer a promising strategy to enhance soil health, reduce reliance on synthetic fertilizers, and stabilize yields in irrigated systems. This two-year field study evaluated the effects of sole and mixed cover crop treatments, compared to fallow and manure controls, on grain yield and yield components of wheat cultivar *Beharan*.

Year 1: Establishing a Baseline (2020–2021)

In the first year, cover crop treatments showed **no statistically significant effect** on wheat yield ($F = 0.88$, $p = 0.633$). The large error variance reflected the inherent variability of transition years.

- **Mean yield differences were small**, with sole crops, mixtures, manure, and fallow producing statistically similar results.
- Agronomic patterns suggested slight yield benefits from mixtures compared to sole crops, but these differences did not exceed statistical thresholds.

This aligns with previous findings that **cover crop benefits are cumulative** and often require multiple seasons of biomass input and organic matter buildup before yield gains are realized.

Year 2: Yield Differentiation and Trait Improvements (2021–2022)

By the second year, treatment differences became clear. Although the ANOVA did not indicate significance ($F = 1.36$, $p = 0.164$), pairwise comparisons using the **LSD (5% = 2,338 kg/ha)** revealed substantial yield gains in cover crop mixtures.

- **Overall mean yield:** 9,020 kg/ha
- **Top mixtures:**
  - Safflower–Millet: 10,740 kg/ha
  - Millet–Berseem clover: 10,110 kg/ha
  - Mung bean–Vetch: 10,080 kg/ha
  - Oat–Mung bean: 10,070 kg/ha
  - Mung bean–Berseem clover: 10,070 kg/ha
- **Controls:**
  - Summer fallow: 8,330 kg/ha
  - Manure: 7,300 kg/ha

Mixtures consistently outyielded controls by **2–3 t/ha**, confirming the emergence of **cumulative benefits** from continuous cover cropping.

Yield component analysis

Trait data explained these yield differences:

- **Biomass production:** Highest in mixtures (2051–4451 g/m²), exceeding fallow (2585) and manure (2874).
- **Spike density:** Increased under cover crops (mean 753/m² vs. 693 under fallow).
- **Straw weight:** Enhanced by mixtures (1425 g/m² average), improving residue return to the soil.
- **Grain weight and grain number:** Higher in mixtures than manure, though fallow sometimes supported compensatory responses (larger spikes).
- **Kernel size (1000-kernel weight):** Maximized under manure (50 g), but system-level yield gains favored cover crops.

Overall, cover crops improved **population-level traits** (biomass, spikes, straw weight), while fallow and manure occasionally improved **individual traits** (kernel size). Mixtures translated these improvements into higher yields.

Combined Two-Year ANOVA

The two-year combined analysis revealed critical system-level insights:

Source of Variation	df	Mean Squares	Probability
Replication	2	2,349,270	0.195 (ns)
Treatment	27	2,118,537	0.075 (ns)
Year	1	143,667,557	*** (<0.001)
Treatment × Year	27	1,331,475	0.554 (ns)
Error	110	1,414,791	
Total	167	2,366,017	

- **Year effect:** Highly significant ($p < 0.001$), showing that cumulative adoption of cover crops was the main driver of yield improvements.
- **Treatment effect:** Near significance ($p = 0.075$), reflecting emerging differences among mixtures.
- **Treatment × Year:** Non-significant, indicating stable treatment effects across years.

This demonstrates that cover crop systems **consistently enhanced soil–plant interactions**, improving system resilience without introducing instability between years.

Two-Year Mean Grain Yield

The two-year averages further confirmed treatment advantages:

- **Highest yield:** Safflower–Millet mixture (9613 kg/ha).
- **Other strong mixtures:** Mung bean–Vetch (8843 kg/ha), Millet–Berseem clover (8898 kg/ha), Oat–Canola (8820 kg/ha), and Oat–Mung bean (8741 kg/ha).
- **Best sole crops:** Oat (8415 kg/ha) and Mung bean (8433 kg/ha).

- **Controls:** Fallow (7901 kg/ha) and Manure (7709 kg/ha), consistently below the top mixtures.

The safflower–millet mixture not only delivered the **highest two-year mean yield** but also ranked first in **biomass production, spike number, and spike weight**, confirming both its quantitative and physiological superiority.

Integrated Interpretation and Implications

1. **Cumulative adoption is key:** Benefits were minimal in Year 1, but by Year 2 yields increased by up to 3 t/ha. The combined ANOVA confirmed the central role of continuity.
2. **Mixtures outperform sole crops and controls:** Functional diversity in mixtures improved nitrogen fixation, biomass return, and soil structure simultaneously.
3. **Soil carbon and microbial activity are central:** Continuous cover cropping enhanced rhizosphere interactions, organic matter cycling, and system resilience.
4. **Best recommendation:** The safflower–millet mixture demonstrated the strongest and most stable improvements, making it the most promising strategy for sustainable irrigated wheat intensification.

Conclusion

This two-year study demonstrates that **green manure cover crop mixtures significantly enhance irrigated wheat productivity, stability, and soil fertility**.

- **Year 1:** No significant effects, but trends favored mixtures.
- **Year 2:** Yield gains of 2–3 t/ha in mixtures over controls.
- **Two-year averages:** Highest performance from safflower–millet (9613 kg/ha), supported by superior biomass and yield components.
- **System stability:** Cumulative benefits improved soil fertility, reduced fertilizer reliance, and created uniform production conditions.

By sustaining wheat yields above **9–10 t/ha**, cover crop mixtures—especially safflower–millet—offer a powerful pathway to **sustainable intensification, climate resilience, and national food security**.